P-ISSN 2586-9000
E-ISSN 2586-9027
Homepage : https://tci-thaijo.org/index.php/SciTechAsia
Science & Technology Asia
Vol.27 No.1 January - March 2022
Page: [100-113]

Original research article

Relationship Between Core Muscle Strength and Power, Pelvis-Hip Biomechanics, and Golf Performance

Piriya Suwondit[1], Plaiwan Suttanon[2], Tanawat Vanasant[3], Sutima Suwankan[1], Vinitha Puengtanom[1], Jakkrapan Chupthaisong[1], Sudarat Apibantaweesakul[1,*]

[1]*Department of Sports Science and Sports Development, Faculty of Allied Health Sciences, Thammasat University, Pathum Thani 12120, Thailand*
[2]*Department of Physical Therapy, Faculty of Allied Health Sciences, Thammasat University, Pathum Thani 12120, Thailand*
[3]*Section of Performance Sports Development, Department of Sports Science, Sports Authority of Thailand, Bangkok 10240, Thailand*

Received 3 October 2019; Received in revised form 19 July 2020
Accepted 20 October 2020; Available online 28 March 2022

ABSTRACT

Biomechanical and physical fitness characteristics, in particular the strength and power of trunk and pelvis are important factors influencing the performance of rapid movements of upper and lower extremities. The golf swing is a rapid movement of upper trunk and upper limb. The objective of this study was to investigate the correlation between core muscle strength and power, pelvis-hip biomechanics, and performance during golf swing. Twenty-two golfers aged from 17 to 33 years participated in this study. Core muscle strength and power were assessed using a medicine ball seated throw and cable weight machine. The biomechanical characteristics of pelvis-hip were recorded by a three-dimensional motion analysis system. A golf simulator was used to measure performance including club head speed, ball speed, and ball distance. Statistically significant correlations were observed between biomechanical characteristics (left hip abduction at top of swing) and golf performances (r = -0.43 to -0.51, $p < 0.05$). Correlations were moderate between physical fitness (core muscle strength and power) and pelvis-hip biomechanical characteristics (r = 0.43-0.54, $p < 0.05$). Our findings demonstrated significant correlations between left hip abduction at top swing and golf performance (focusing on ball speed and driving distance) as well as core muscle strength/power and pelvis-hip biomechanics including X-factor. Therefore, improvement of these variables may enhance performance by controlling the stability of the trunk and pelvis which in turn could lead to a more effective golf swing.

Keywords: Core muscle strength; Golf biomechanics; X-factor

***Corresponding author:** thamms11@hotmail.com
doi: 10.14456/scitechasia.2022.10

1. Introduction

Golf is a sport and leisure activity that is available to a wide age range, from children to elderly people. The golf swing has evolved over time, following the results of research in the area of sports science [1-3]. Previous studies have found that biomechanics of the trunk and pelvis, and physical fitness were correlated to golf swing performance [1, 3-5]; however, correlations among these parameters were unclear and limited, especially regarding the relationship between pelvis-hip biomechanics and golf-related physical fitness of core muscles. The effectiveness of the golf swing can be evaluated by club head speed, ball speed, driving distance, and launch angle [1-3, 6-7]. The trunk-pelvis biomechanical parameters including upper-torso rotation, X-factor (hip-shoulder relationship), O-factor (pelvic obliquity), and S-factor (shoulder obliquity) are the movements in the transverse/diagonal plane that may be involved in golf swing power, be affected by the training program, and play a role in injury prevention [1, 4, 8]. The X-factor has been mentioned in previous studies and was first introduced by Jim McLean [8-11], and is described as the relationship between rotation angle of shoulder and hip lines at the top of the backswing [8-9]. According to the stretch-shortening cycle, pelvic movement is stabilized and the upper body is twisted (stretching phase) in the backswing phase, then power is produced by the rapid downswing (shortening phase) [9-10]. The biomechanics of the hip and pelvis in the transverse plane, including X- factor, are essential for transferring force to club head and generating ball speed via the theory of kinetic chain and core stability [12-13]. However, the effect of the X-factor on golf performance has only been critically evaluated in some studies [6, 8]. The biomechanics of the trunk, hip, and pelvis are crucial to golf performance, as well as to physical fitness including flexibility, muscular strength, endurance, balance, stability, and cardiovascular capability [4-5, 14-15]. Specific physical fitness tests were developed in order to evaluate and contribute to golf training programs, such as the isoinertial test [14], core stability test [16], balance test [17-18], and flexibility test [15]. Isoinertial condition has been assessed with constant gravitational load and dynamic movement, for example by total body rotational power, medicine ball seated throw performance, and cable weight machine performance. In addition, the core stability of golfers has been assessed by strength and power performance [15, 19]. Apart from that, muscle endurance, balance, and flexibility have all been found to be important to golf performance [16-18, 20]. Biomechanics of golf swing and physical fitness in lumbopelvic- hip have been widely investigated for the purpose of improving performance and preventing injury. However, understanding of the relationships between these parameters is unclear and limited. To gain a better understanding, we investigated the correlations between pelvis-hip biomechanics and golf-related physical fitness of core muscles that may be beneficial to golf performance. Therefore, the purpose of the present study was to establish the relationship between physical fitness (core muscle strength and power), golf swing biomechanics (focusing on the trunk-pelvic-hip region), and golf performance.

2. Materials and Methods

2.1 Participants

Twenty-two healthy golf athletes (19 male and 3 female) aged 17 to 33 years participated in this study. All athletes voluntarily participated and signed an informed consent document in addition to completing a health history questionnaire and physical examination screening before all measurements. This study was approved by the Ethical Committee on Research Involving Human Subjects, Thammasat University (COA 025/2558). Participants were excluded from this study if they reported any of the following criteria: a) low back pain within the previous month, b) abdominal or back surgery within the last three months, and c) any musculoskeletal problem that might affect the test results.

2.2 Experimental procedures

Each participant had to follow a warm-up stretching routine before data collection. The data collection consisted of biomechanical, golf performance, and physical fitness measurements. Two biomechanics parameters, joint angles of hip-pelvis and X-factor (defined as differential angle between both hip markers and both shoulder markers), were measured and analyzed using an 8-camera Vicon motion analysis system (Vicon MX 512 M, OMG, Oxford, UK) with a sampling rate of 250 Hz. Simultaneously, the golf performance was recorded by a simulator sensor and 12-point swing analysis software (P3 Simulator ProX Studio Package, US). In this study we focused on club head speed, ball speed, and driving distance as indicators of golf performance. Participants were instructed to perform two sessions, warm up (submaximal effort) and then maximal effort. In each set, the participants performed five golf swings with their own driver and the same brand of golf ball. Participants were allowed to rest for three minutes between sets and one minute between trials. Then after a rest of five minutes, physical fitness was assessed by measuring the distance of front and side abdominal (core) strength, and power was assessed by measuring the maximum weight that could be lifted from a golf swing-specific cable wood chop. Before and after physical fitness and functional testing, the participants were instructed to perform a stretching session to prevent injury.

2.2.1 Three-dimensional motion and golf performance measurements

All participants were required to wear tight cloth for identifying specific anatomical landmarks. Thirty-eight markers (following 36 markers on the body with respect to the Vicon Plug-In Gait model and 2 markers on the club head and the shaft) were attached and their respective software (Nexus 1.4 116, Oxford, UK) was used to capture and analyze the golf swing trials. Hip and pelvis joint angles (including hip flexion/extension, hip abduction/adduction, and pelvic anterior/ posterior tilt), and X-factor were evaluated in each phase of golf swing ((1) address position-start position where the golfer prepares to hit the ball, (2) top of swing-at the end with the club parallel to the ground after the club is brought backwards, (3) impact point-the club hits the ball, and (4) end of follow through-at the end of forward club swing in the follow through and finish. The golf swings were performed in a laboratory with a net located 2.5 meters ahead. The sensor for assessing golf performance was set up as the ground. The shot with the highest performance was selected for analysis including ball speed, club head speed, and driving distance (from club head hitting the ball to the ball hitting the floor). In addition, golfers' handicaps were recorded in order to represent the level of athletic performance.

2.2.2 Core muscle strength and power measurements

Front abdominal power (adapted from Cowley and Swensen [21])
Starting position: Supine with 90 degrees of knee flexion, straight arms holding medicine ball overhead. (2 kg for female, 3 kg for male)
Protocol: Participants quickly sat up with straight arms and released the ball when they were over the knees.
Outcome measurement: Maximum medicine ball distance (measured from the tip of the feet to where the medicine ball landed) was used for analysis.

Side abdominal power (adapted from Cowley and Swensen [21])
Starting position: Sitting with 90 degrees of hip flexion and 90 degrees of knee flexion, straight arms holding medicine ball in front of body (2 kg for female, 3 kg for male)

Protocol: Participants lean backwards until the hip angle was 45 degrees, with straight arms, then slowly rotate the trunk to the right by 90 degrees. After that the participant was asked to rapidly rotate to the left and release the ball when they were over the left knee. Test was repeated but in the opposite direction (i.e., rotation to the left, then to the right).
Outcome measurement: Maximum medicine ball distance was measured from the tip of the feet to where the medicine ball landed and used for analysis

Muscle strength using golf swing-specific cable wood chop [20].
Starting position: Using a dual adjustable pulley in golf backswing position (grabbing the cable with both hands).
Protocol: Participants performed a downswing with cable resistance 3-6 RM. If more than 6 repetitions were performed, the golfer rested for 2 minutes and then performed the same exercise with a heavier load that would likely result in failure in 3–6 repetitions.
Outcome measurement: Resistance was converted to 1 RM.
(1RM = mass lifted/1.0278-0.0278 [number of repetitions])

For the physical fitness parameters including core muscle strength and power, the data were normalized by body mass.

2.3 Statistical Analysis

A power analysis calculated for this study, based on the effect size of a previous study [8], indicated that a minimum sample size of 22 participants would be required to detect a significant difference for correlation between core muscle strength and power, pelvis-hip biomechanics, and golf performance, at 80% power and an α error probability=0.05. For the recorded parameters the mean values and standard deviations were calculated. Correlation coefficients were determined between parameters by Spearman's Correlations at a significant level of 0.05.

3. Results and Discussion

3.1 Characteristics of participants

Twenty-two golfers participated in this study and their basic characteristics are presented in Table 1 The majority of participants were male (19 males and 3 females, 86.36% and 13.63, respectively). Prior studies supported that gender could influence physical fitness and also possibly golf performance [18], while differences in golf biomechanics between males and females were still inconclusive. In this study, there were significant differences found between genders in only a few variables (LtHip_AP4, RtHip_ML3, LtHip_ML3, LtHip_ML4) from a total of 21 biomechanical variables. Also, there were significant differences in all golf performance variables. Since we included both males and females in the analyses, we normalized data by body mass in order to minimize the possibility that gender would influence the results. We aimed to investigate correlation in areas where we expected to see various levels of performance; 4 participants reported as professional golfers, 15 participants reported a handicap of 0-15, and 3 participants reported a handicap > 15. All participants presented left leg as their lead leg.

Table 1. Characteristics of participants (n = 22).

Descriptive variables	Mean ± SD	Minimum	Maximum
Age (years)	20.95 ± 4.27	17	33
Weight (kg)	70.31 ± 15.88	46.50	105.00
Height (cm)	174.45 ± 7.73	158.00	188.00
Experience (years)	8.50 ± 4.83	1	22
Handicap	7.52 ± 10.78	-3.5	36

3.2 Golf performance and physical fitness

The recorded golf performance and physical fitness values of the participants are shown as minimum, maximum, and mean including standard deviation in Tables 2 and 3. Golf performance values are shown as club head speed, ball speed, and distance (Table

2). Physical fitness values (strength and power) are shown as front abdominal power, right and left side abdominal power, and golf swing-specific cable wood chop performance for total body strength (Table 3).

Table 2. Golf performance of participants.

Golf performance variables	Mean ± SD	Minimum	Maximum
Club head speed (mph)	97.64 ± 10.89	69.70	111.50
Ball speed (mph)	139.92 ± 15.66	95.00	160.50
Distance (yard)	246.01 ± 28.50	176.70	283.10

Table 3. Physical fitness and normalized values.

Physical fitness variables	Mean ± SD	Minimum	Maximum
Front abdominal power (cm)	135.93 ± 79.50	48.00	268.00
Normalized value (cm/kg)	2.03 ± 1.28	0.63	4.94
Right side abdominal power (cm)	298.79 ± 86.66	141.00	455.00
Normalized value (cm/kg)	4.43 ± 1.64	2.15	8.25
Left side abdominal power (cm)	294.02 ± 81.75	165.00	434.00
Normalized value (cm/kg)	4.35 ± 1.48	1.81	7.08
Golf swing specific cable wood chop (kg)	26.94 ± 6.71	16.36	37.75
Normalized value	0.39 ± 0.09	0.26	0.56

In this study, 54.50% of participants were aged less than 20 years and the majority of participants were in the amateur group. The results of this study showed a lower golf performance compared to previous studies [18, 22-24]. That might be why our results found a correlation with golf performance only in the pelvis-hip biomechanical characteristics. Therefore, the golfers in our study might be influenced by the swing technique and possibly less reliant on physical fitness characteristics. In previous studies it has been reported that concentric strength tends to peak between 20 and 30 years of age, then plateaus until about 50 (in men) and then declines at a rate of 12–15% per decade [25-27]. Previous studies have shown a difference in muscle performance between males and females, females being lower [28, 29]. We conducted data sub-analysis by excluding the 3 females and found that golf performance slightly increased (approximately 2%). However, these physical performance results still would be considered lower compared to previous studies. Thus, the data from the 3 females remained in the study. However, a previous study did not find sex-specific differences in the pelvis, thorax, or shoulder kinematic variables [24]. The comparatively lower weight and height of this study's participants compared with previous studies might have impacted results for physical fitness, in particular muscle performance, found in this study [22]. Results of physical fitness in this study were lower than what had been reported in previous studies that investigated physical fitness in golfers [20, 21]. Accordingly, this study normalized the physical fitness parameters by body mass to diminish the influence of individual factors.

3.3 Correlations between physical fitness characteristics (core muscle strength and power) and golf performance

It is important to note that all physical fitness variables were normalized by body mass for this analysis. The results showed no significant correlations between physical fitness and golf performance parameters (club head speed, ball speed, distance) in this study (Table 4).

Table 4. Correlation coefficients between normalized core muscle strength/power and golf performance.

Physical fitness \ Golf performance	Club head speed (mph)	Ball speed (mph)	Distance (yd)
Front abdominal power (cm/kg)	-0.352	-0.296	-0.325
Right side abdominal power (cm/kg)	-0.152	-0.138	-0.165
Left side abdominal power (cm/kg)	-0.151	-0.157	-0.179
Golf swing specific cable wood chop (1 RM/kg)	-0.164	-0.149	-0.152

Spearman's Correlation, *: significant at $p < 0.05$, **: significant at $p < 0.01$

In this study, no significant correlations were found between physical fitness and golf performance parameters. The effect size calculated by the coefficient of determination was found to be a small effect (<0.10-0.12) according to Cohen's guidelines [30]. However, golf performance might not only be influenced by physical fitness, but also by other factors including biomechanical characteristics, which are related to individual skill and technique [13, 31-32]. According to the results of this study, there was no significant correlation between golf performance and physical fitness. Only biomechanical characteristics were found to be significantly correlated with golf performance. Thus, skillful movement and appropriate biomechanical characteristics highly influence golf performance in Thai golfers. Furthermore, our study focused on muscle strength and power as physical fitness characteristics. Thus, our physical fitness tests were selected to be specific for golf, such as the golf swing-specific cable wood chop which is considered to be a sequential movement with power development beginning with ground reaction forces in the lower extremities and peaking at club head impact. Furthermore, the front and side abdominal power tests separated core and trunk muscle measurements. Skilled golfers would have optimal swing mechanics that might effect golf performance more so than physical fitness characteristics [22]. This could be an explanation for the non-significant correlations between physical fitness characteristics (core muscle strength and power) and golf performance found in this study. Results of previous studies support the presence of a correlation between golf performance and physical fitness focusing on strength, power, endurance, and flexibility [18, 22]. The physical fitness characteristic most frequently found to be correlated with club head speed is total body rotational power, measured by tests such as the golf swing-specific cable wood chop [15, 20, 22]. Possible explanations for the absence of correlation in the current study could include the influence of arm (lever) length on the golfers' moment of force that resisted the pulling cable movement, as golfers with shorter arms might have an advantage [20, 31]. On the other hand, if two golfers have the same core muscle fitness, a longer armed golfer might generate greater club head speed than a shorter armed golfer. Another explanation could be that although the golf swing-specific cable wood chop closely matches the movement pattern of the golf swing, some golfers might not be familiar with the cable crossover machine. Therefore, the difference in training patterns might affect the difficulty of performing the golf swing- specific cable wood chop test. In addition, a correlation between golf performance and muscle strength was also found for different body parts such as torso rotation [33], peripheral muscle strength (consisting of vertical jump, pull up, push up, and arm grip strength), ball speed, carry distance, tournament performance [18], chest strength [15], and hip and shoulder strength [33]. On the other hand, there was no significant correlation between peripheral muscle strength (grip strength, bench press 1 RM, squat 1 RM, lat pull 1 RM, shoulder press 1 RM, hack squat, and isometric prone hold) and club head speed [20, 22]. This study focused on core muscle strength and power in terms of physical fitness characteristics. However, there were only a few literature reviews in this area of study and the relationship between core muscle performance and golf performance was not clear. In this study, the front and side abdominal medicine ball tests focused on core muscle strength and power by reducing confounding factors from lower limb and upper limb muscle strength that could have otherwise affected the results. The results did not show any relation between muscle performance and golf performance. This might be due to an unfamiliarity with the ball release method golfers were instructed to perform. The release method consisted of an explosive concentric contraction of the abdominal and hip flexor muscles, while using the arms as a lever to project the medicine ball without intimately using the shoulders for the throwing. Similar to the golf swing-specific cable wood chop [20], the length of arm lever was positively correlated to medicine ball angular velocity. Although no correlations were found, the results of previous studies suggest that muscle strength and power may have some benefit for golfers, such as low back pain prevention [34-35].

3.4 Correlations between pelvic- hip biomechanical characteristics and golf performance

The correlation coefficients between biomechanical characteristics and golf performance in Table 5 show the correlation coefficients between hip angles in the frontal plane during four phases of golf swing (address, top swing, impact point, and end of follow-through) with a small effect size (<0.10-0.19) [30]. This study did not find significant correlations between X-factor (upper torso-pelvis separation), hip flexion/extension, pelvic tilt, and golf performance. However, moderate correlations were noted between left hip abduction at top swing and golf performance (focusing on ball speed and driving distance). The hip joint angle in the mediolateral direction at top backswing was correlated with ball speed and distance (r = -0.431, p =0.045 and r = -0.441, p = 0.040, respectively).

Table 5. Correlation coefficients between biomechanical characteristics (X-Factor, hip and pelvic angles), and golf performance.

Golf performance / Biomechanical variables	Club head speed (mph)	Ball speed (mph)	Distance (yd)
X-Factor	-0.107	-0.125	-0.147
RtHip_AP1	-0.170	-0.081	-0.063
RtHip_AP2	-0.074	0.021	0.028
RtHip_AP3	-0.344	-0.300	-0.309
RtHip_AP4	-0.252	-0.186	-0.207
LtHip_AP1	-0.036	0.056	0.051
LtHip_AP2	0.013	0.109	0.094
LtHip_AP3	-0.119	-0.081	-0.093
LtHip_AP4	0.011	0.057	0.034
RtHip_ML1	-0.204	-0.254	-0.258
RtHip_ML2	0.086	0.023	0.053
RtHip_ML3	0.289	0.228	0.214
RtHip_ML4	-0.095	-0.092	-0.128
LtHip_ML1	0.030	0.076	0.084
LtHip_ML2	-0.359	**-0.431***	**-0.441***
LtHip_ML3	-0.179	-0.135	-0.126
LtHip_ML4	-0.413	-0.377	-0.383
Pelvic_AP1	-0.088	-0.045	-0.045
Pelvic_AP2	0.014	0.004	0.004
Pelvic_AP3	-0.244	-0.167	-0.169
Pelvic_AP4	0.120	0.231	0.206

Spearman's Correlation, *: significant at $p < 0.05$, **: significant at $p < 0.01$
RtHip_ML: Right hip Adduction/Abduction, LtHip_ML: Left hip Adduction/Abduction
RtHip_AP: Right hip flexion/extension, LtHip_AP: Left hip flexion/extension
Pelvic_AP: Pelvic anterior/posterior tilt
The four phases of golf swing consist of 1=Address, 2=Top swing, 3=Impact point, 4=End of follow through

Among the analyzed biomechanical variables of hip and pelvic angles, only hip abduction angle was found to be significantly correlated with golf performance. A previous study [9] showed that the right hip was significantly more abducted in the high golf performance group, while there was not a significant difference of left hip abduction between the 2 performance groups. Moreover, left hip at the top of back swing was indicated as the maximum abduction angle with greater values seen in high ball speed group [36].The movement of the hip in the frontal plane represented transferring a greater amount of weight from left to right foot in the high ball speed group, from top swing to impact phases [9]. Weight transfer in the golf swing is considered important in coaching terms, with the main sequence as 1) weight balanced between the feet at address, 2) weight is moved towards the right foot (trail foot) during the backswing, 3) during the downswing phase, weight is transferred towards the left foot (lead foot), and then weight is positioned on the lead foot at ball impact and follow through [37-39]. Our findings support that left hip abduction at top swing is related to golf performance and should be noted as the essential movement for transferring weight in the golf swing. This weight transfer would aid the generation of greater ball speed and improve related golf performance [9]. Although, our study did not show significance in the same phase of the golf swing as another study. This might be caused by the fact that in the previous study there was no handicap recorded as an indicator of golf performance, rather golfers were divided into high and low ball speed groups; this could have resulted in golfers who had high ball speed but an incorrect manner of golf swing. Other possibilities include ethnic differences and different types of golf clubs used (driver vs 5 iron). Moreover, other studies might have defined that there was more than the right hip abduction during down swing but it would add the left hip adduction during top backswing as one of the effective movements of golf swing [36].

3.5 Correlations between biomechanical (X-Factor, hip and pelvic angles) and physical fitness characteristics

The correlation coefficients between biomechanical and physical fitness characteristics are presented in Table 6. Moderate correlations were found between physical fitness and biomechanical variables including hip abduction/adduction, pelvic angles, and X-factor. The effect size was found to be small (<0.01 – 0.29) [30]. The X-factor was significantly correlated with side abdominal power maximum (R), and golf swing- specific cable wood chop (r = 0.481 and 0.499 respectively, $p < 0.05$). There were moderate correlations between left hip adduction at impact point and physical fitness characteristics (front abdominal power maximum and left side abdominal power maximum (r = 0.440 and 0.440 respectively, $p<0.05$). Furthermore, pelvic movement in the anteroposterior direction at the end of the follow-through phase correlated with front abdominal power maximum (r = 0.430, $p<0.05$), and both sides of abdominal power maximum ((R) r = 0.543, (L) r = 0.511, $p<0.05$). Performance in golf is influenced by biomechanical characteristics including rotational body movement, that both transfers and contributes energy and force from the ground through the core, upper extremities, the club, and the ball [1, 2, 12]. Therefore, core strength and power are crucial to stabilize the hips and spine, to improve body control during golf swing, and also to generate force to the ball [40]. The findings of this study support the presence of correlations between biomechanics and core muscle performance. Hip abduction/adduction angles were found to be correlated with core power in which the main muscles (trunk extensors and abdominal oblique) affecting core muscle power corresponded to the muscles used during ball impact and consequently might cause left hip adduction [39, 41]. Therefore, having core power, especially the internal and external oblique muscles while testing the front and side medicine ball throw would help swing mechanics during ball impact [42]. For this reason, trunk muscles are recognized to facilitate left hip adduction. The trunk muscles, especially the erector spinae muscles and the abdominal oblique muscles, act to maintain body posture during the acceleration phase [32, 39]. During the early downswing phase, the movement is initiated by the hips, pelvis rotation, and weight shift toward the hip extensor and abductors on the trail leg (right leg), and hip adductor on the lead leg [39]. Additionally, hip function including hip flexor, extensor, and abductor influenced body sway and postural control [43-45]. The X-factor was considered to fit well with the clinical perspective. In the acceleration phase of the downswing, the ability to quickly rotate the torso is a key element to performance [46]. Research has also shown upper torso rotation velocity to be the most important predictor of acceleration [31]. Moreover, the current study also found a correlation between X-factor and core power and strength. This could imply that increased X-factor assists in improving both core strength and power [47] in which the pelvis is stabilized (hip line), while the upper body rotates during the back swing phase (stretching phase). These influence the power in downswing phase (shortening phase) [9, 10]. Although it seems an increased x-factor would benefit power and strength, some studies suggest that x-factor might be a risk factor of low back pain and might not be an important performance indicator [34, 48]. Thereby, this study did not show the correlation between x-factor and any golf performance. This could also be explained by the relationship between range of motion and muscle strength and power. Regarding the importance of flexibility, the effect of muscle length on the effective explosiveness of muscles should be noted, as utilizing the full length of the muscle might be a component of exerting power and thus the ability to reach peak performance. Focusing on golf swing, trunk tightness, and pelvic and shoulder rotation would not allow a golfer extra stretch on the muscles during backswing and downswing. This would affect golf performance and impede other correlations. The findings of the current study demonstrate a correlation between pelvic tilt and core power. This positive correlation implies that increased core power would result in increased anterior pelvic tilt during the end of the follow-through phase. This correlation could be partly explained by the fact that the modern golf swing is often promoted over the more relaxed classic swing, as it is believed to utilize elastic energy stored in skeletal muscles to increase power [34] which finishes in lumbar hyperextension (Reverse-C position with hip extend and anterior pelvic tilt) which might increase pressure on the spine [9, 35]. Adding to the injury potential during follow-through are the eccentrically contacting abdominal muscles used to slow rotation, which increase pressure on the annulus of the intervertebral disc [35, 49]. Thus, good core muscle power helps prevent injury from this issue [35, 40], and is attributed to an effective golf swing during the end of the follow through phase. As our study demonstrated the relationship between core power and anterior pelvic tilt at the end of follow through, it follows that anterior pelvic tilt may be easier and safer. Tightness of the muscles associated with controlling pelvic tilt such as the hamstring, psoas muscles and quadratus lumborum [50], biceps femoris and iliopsoas, are a common finding in low back pain. This could be due to overuse or postural shortening and restricted motion at the hip joint [51] (the iliopsoas helps maintain posture for hip flexion during the golf swing). Consequently, muscular inflexibility might cause pain and affect a golfer’s swing mechanics; golfers may be at risk for development of neck, shoulder, and torso muscle injuries affected by poor body alignment [52] that affect the ability to move and control the position of the pelvis, a component critical for optimal power transfer from the lower body to the upper body during the golf swing [53]. Eventually, if the pelvis isn’t in this way, most of the force of rotation goes in to the back, causing pain during the golf swing. In addition, compared with previous studies [21], the mean distance found for the front abdominal power test was lower (Table 3), therefore less power of the rectus abdominis was found in the participating golfers in this study. Imbalance between anterior pelvic tilt muscles and posterior pelvic tilt muscles disturbed lumbopelvic postural control in the sagittal plane [54], these muscles may contribute to movement during the golf swing in a multi-dimensional movement plane. Therefore, balance of core muscle strength with good mobility and flexibility would help to maintain a correct neutral position during both static and dynamic conditions [32, 40].

Additionally, the testing protocol for measuring core muscle power utilized in this study used a sitting position, which mainly focused on trunk muscle performance. The other test used a supine position that mainly focused on the strength and power component of the rectus abdominis and trunk flexion movement. However, there was no relationship between the front abdominal power test and the pelvic-hip biomechanical characteristics in the sagittal plane direction (hip flexion/extension). Furthermore, golf practice is performed in a standing position and core muscle power is influenced not only by trunk muscles, but also lower extremity muscles, in particular the hip muscles. Therefore, measuring core muscle power in a standing position [55-56] assists in keeping the hip flexion still, similar to the position taken when a golfer addresses the ball. Additionally, throwing the medicine ball from right to left and downswing maximize striking skill performance and kinetic energy [57]. This would possibly result in a better picture of the correlation between core muscle power and hip and pelvic angles in golfers. Lastly, further study should consider possible confounding factors (i.e., arm length, flexibility, balance, coordination, and mobility) that might influence muscle strength and power measurements, consequently effecting golf performance.

Table 6. Correlation coefficients between X-Factor, hip and pelvic angles, and normalized core muscle strength/power.

Physical fitness / Biomechanics variables	Front abdominal power (cm/kg)	Side abdominal power R (cm/kg)	Side abdominal power L (cm/kg)	Golf swing specific cable wood chop (1 RM/kg)
X-factor	0.003	**0.481***	0.371	**0.499***
RtHip_AP1	0.176	-0.027	0.029	0.028
RtHip_AP2	0.057	-0.173	-0.240	-0.233
RtHip_AP3	0.179	-0.016	-0.122	-0.137
RtHip_AP4	0.203	-0.084	-0.153	-0.217
LtHip_AP1	0.395	0.240	0.302	0.028
LtHip_AP2	0.296	0.108	0.063	-0.003
LtHip_AP3	0.078	-0.013	-0.136	-0.339
LtHip_AP4	-0.123	-0.256	-0.272	-0.395
RtHip_ML1	-0.036	0.151	0.130	0.006
RtHip_ML2	-0.270	0.056	0.094	-0.147
RtHip_ML3	-0.197	-0.345	-0.250	-0.015
RtHip_ML4	-0.006	-0.117	-0.091	-0.100
LtHip_ML1	0.067	-0.084	-0.054	-0.003
LtHip_ML2	-0.001	0.049	0.049	0.170
LtHip_ML3	**0.440***	0.366	**0.440***	0.303
LtHip_ML4	0.214	0.195	0.250	-0.003
Pelvic_AP1	0.266	0.082	0.158	0.216
Pelvic_AP2	0.138	-0.269	-0.122	-0.075
Pelvic_AP3	0.416	0.004	0.050	-0.092
Pelvic_AP4	**0.430***	**0.543****	**0.511***	0.252

Spearman's Correlation, *: significant at $p< 0.05$, **: significant at $p< 0.01$
RtHip_ML: Right hip Adduction/Abduction, LtHip_ML: Left hip Adduction/Abduction
RtHip_AP: Right hip flexion/extension, LtHip_AP: Left hip flexion/extension
Pelvic_AP: Pelvic anterior/posterior tilt
The four phases of golf swing consist of 1=Address, 2=Top swing, 3=Impact point, 4=End of follow through.

4. Conclusion

In the participating Thai golfers, golf performance was found to be more dependent on the investigated biomechanical variables than on physical fitness, especially biomechanics of left hip angles (lead leg) in the medio-lateral plane (abduction/adduction). Even though physical fitness might not be directly correlated with golf performance, physical fitness is still an important factor that influences golf performance as it is correlated to the biomechanics of hip and pelvis, and the X-factor.

Acknowledgements

This study was supported by the Sports Authority of Thailand, and Department of Sports Science and Sports Development, Faculty of Allied Health Sciences, Thammasat University.

References

[1] Meister DW, Ladd AL, Butler EE, Zhao B, Rogers AP, Ray CJ, et al. Rotational biomechanics of the elite golf swing: benchmarks for amateurs. J Appl Biomech 2011;27(3):242-51.

[2] Nesbit SM. A three dimensional kinematic and kinetic study of the golf swing. J Sports Sci Med 2005;4:499-519.

[3] Myers J, Lephart S, Tsai YS, Sell T, Smoliga J, Jolly J. The role of upper torso and pelvis rotation in driving performance during the golf swing. J Sports Sci 2008;26(2):181-8.

[4] Tsai YS, Sell TC, Smoliga JM, Myers JB, Learman KE, Lephart SM. A Comparison of Physical Characteristics and Swing Mechanics between Golfers with and without a History of Low Back Pain. J Orthop Sports Phys Ther 2010;40:430-8.

[5] Callaway S, Glaws K, Mitchell M, Scerbo H, Voight M, Sells P. An analysis of peak pelvis rotation speed, gluteus maximus and medius strength in high versus low handicap golfers during the golf swing. Int J Sports Phys Ther 2012;7:228-95.

[6] Kim YS, So JM. An Analysis of X-Factor, Triple X-Factor, and the Center of Pressure (COP) according to the Feel of the Golf Driver Swing. KJSB 2016;26(3):265-72.

[7] Sinclair J, Currigan G, Fewtrell DJ, PJ T. Biomechanical correlates of club-head velocity during the golf swing. Int J Perform Anal Sport 2014;14:54-63.

[8] Cole M, Grimshaw P. The X-Factor and its relationship to golfing performance. J Quant Anal Sports 2009;5(1):1-19.

[9] Healy A, Moran K, Dickson J, Hurley C, Smeaton A, OConnor NE, et al. Analysis of the 5 iron golf swing when hitting for maximum distance. J Sports Sci 2011;29(10):1079-88.

[10] An J, Wulf G, Kim S. Increased Carry Distance and X-Factor Stretch in Golf Through an External Focus of Attention. J Mot Learn Dev 2013;1:2-11.

[11] Joyce C, Burnett A, Ball K. Methodological considerations for the 3D measurement of the X-factor and lower trunk movement in golf. Sports Biomech 2010;9(3):206-21.

[12] Hume PA, Keogh J, Reid D. The Role of Biomechanics in Maximising Distance and Accuracy of Golf Shots. Sports Med 2005;35(5):429-49.

[13] Lindsay DM, Mantrop S, Vandervoort AA. A Review of Biomechanical Differences Between Golfers of Varied Skill Levels. Int J Sports Sci Coach 2008;3:187-97.

[14] Torres-Ronda L, Sánchez-Medina L, González-Badillo JJ. Muscle strength and golf performance: A critical review. J Sports Sci Med 2011;10:9-18.

[15] Gordon BS, Moir GL, Davis SE, Witmer CA, Cummings DM. An investigation into

the relationship of flexibility, power, and strength to club head speed in male golfers. J Strength Cond Res 2009;23(5):1606-10.

[16] Okada T, Huxel KC, Nesser TW. Relationship between core stability, functional movement, and performance. J Strength Cond Res 2011;25(1):252-61.

[17] Wells GD, Elmi M, Thomas S. Physiological correlates of golf performance. J Strength Cond Res 2009;23:741-50.

[18] Wells GD, Elmi M, Thomas S. Physiological correlates of golf performance. J Strength Cond Res 2009;23(3):741-50.

[19] Read PJ, Lloyd RS, Croix MDS, Oliver JL. Relationships between field-based measures of strength and power and golf club head speed. J Strength Cond Res;27(10):2708-13.

[20] Keogh JW, Marnewick MC, Maulder PS, Nortje JP, Hume PA, Bradshaw EJ. Are anthropometric, flexibility, muscular strength, and endurance variables related to clubhead velocity in low- and high-handicap golfers? J Strength Cond Res 2009;23(6):1841-50.

[21] Cowley PM, Swensen TC. Development and reliability of two core stability field tests. J Strength Cond Res 2008;22(2):619-24.

[22] Doan BK, Newton RU, Kwon YH, Kraemer WJ. Effects of physical conditioning on intercollegiate golfer performance. J Strength Cond Res 2006;20(1):62-72.

[23] Fletcher IM, Hartwell M. Effect of an 8-week combined weights and plyometrics training program on golf drive performance. J Strength Cond Res 2004;18(1):59-62.

[24] Parker J, Lagerhem C, Hellstrom J, Olsson MC. Effects of nine weeks isokinetic training on power, golf kinematics, and driver performance in pre-elite golfers. BMC Sports Sci Med Rehabil 2017;9:21.

[25] Plato CC, Kallman DA, Tobin JD. The Role of Muscle Loss in the Age-Related Decline of Grip Strength: Cross-Sectional and Longitudinal Perspectives. J Gerontol A Biol Sci Med Sci 1990;45(3):M82-M8.

[26] Larsson L, Grimby G, Karlsson J. Muscle strength and speed of movement in relation to age and muscle morphology. J Appl Physiol Respir Environ Exerc Physiol 1979;46(3):451-6.

[27] Men Y, Young A, Stokes M, Crowe M. The size and strength of the quadriceps muscles of old. Clin Physiol 1985;5(2):145-54.

[28] Hurley BF. Age, gender, and muscular strength. J Gerontol A Biol Sci Med Sci 1995;50 Spec No:41-4.

[29] Danneskiold-Samsoe B, Bartels EM, Bulow PM, Lund H, Stockmarr A, Holm CC, et al. Isokinetic and isometric muscle strength in a healthy population with special reference to age and gender. Acta Physiol (Oxf) 2009;197 Suppl 673:1-68.

[30] Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, N.J.: L. Erlbaum Associates; 1988.

[31] Chu Y, Sell TC, Lephart SM. The relationship between biomechanical variables and driving performance during the golf swing. J Sports Sci 2010;28(11):1251-9.

[32] Hume PA, Keogh J, and Reid D. The role of biomechanics in maximizing distance and accuracy of golf shots. Sports Med 2005;35:429-49.

[33] Sell TC, Tsai YS, Smoliga JM, Myers JB, Lephart SM. Strength, flexibility, and balance characteristics of highly proficient golfers. J Strength Cond Res 2007;21(4):1166-71.

[34] Cole MH, Grimshaw PN. The Biomechanics of the Modern Golf Swing: Implications for Lower Back Injuries. Sports Med 2016;46(3):339-51.

[35] Finn C. Rehabilitation of low back pain in golfers: from diagnosis to return to sport. Sports health 2013;5(4):313-9.

[36] Healy A. Identification of the biomechanical performance determining factors of the 5 iron golf swing when hitting for maximum distance: Dublin City University; 2009.

[37] Ball K. Weight transfer styles in the golf swing : individual and group analysis. Australia: Victoria University; 2006.

[38] Paiva M, Gonçalves P, Sousa F, Machado L, Vilas-Boas JP. 3D kinematic and kinetic analyses of the golf swing using three different clubs: A case study. Revista Portuguesa de Ciências do Desporto 2011;11:44-58.

[39] Magee DJ, Zachazewski JE, Quillen WS, Manske RC. Athletic and Sport Issues in Musculoskeletal Rehabilitation - E-Book: Elsevier Health Sciences; 2010.

[40] Datta A, Sen S, Shivpriya. Effects of Core Strengthening on Cardiovascular Fitness, Flexibility and Strength on Patients with Low Back Pain. J Nov Physiother 2014;2:202.

[41] Burden AM, Grimshaw PN, Wallace ES. Hip and shoulder rotations during the golf swing of sub-10 handicap players. J Sports Sci 1998;16(2):165-76.

[42] Moore KL, Dalley AF, Agur AMR. Clinically Oriented Anatomy: Wolters Kluwer Health/Lippincott Williams & Wilkins; 2013.

[43] Sarabon N, Hirsch K, Majcen Rošker Ž. The acute effects of hip abductors fatigue on postural balance. MJSSM 2016;5:5-9.

[44] Park Hj, Cho Sh. Effect of Hip Flexion and Internal Rotation on the Hip Abductor Muscle Activity During Side-Lying Hip Abduction in Subjects With Gluteus Medius Weakness. PTK 2016;23(3):57-67.

[45] McMullen KL, Cosby NL, Hertel J, Ingersoll CD, Hart JM. Lower extremity neuromuscular control immediately after fatiguing hip-abduction exercise. J Athl Train 2011;46(6):607-14.

[46] McHardy A, Pollard H. Muscle activity during the golf swing. Br J Sports Med 2005;39(11):799-804.

[47] Cole MH, Grimshaw PN. The X-Factor and Its Relationship to Golfing Performance. J Quant Anal Sports 2009;5(1):1-19.

[48] Cole MH, Grimshaw PN. The crunch factor's role in golf-related low back pain. Spine J 2014;14(5):799-807.

[49] Brandon B, Pearce PZ. Training to prevent golf injury. Curr Sports Med Rep 2009;8(3):142-6.

[50] Zawadka M, Skublewska-Paszkowska M, Gawda P, Lukasik E, Smolka J, Jablonski M. What factors can affect lumbopelvic flexion-extension motion in the sagittal plane?: A literature review. Hum Mov Sci 2018;58:205-18.

[51] McGregor AH, Hukins DW. Lower limb involvement in spinal function and low back pain. J Back Musculoskelet Rehabil 2009;22(4):219-22.

[52] Dale RB, Chen B, Lam WK, Mok D, Yeung F, Hung J. A Three-Week Conditioning Program for Improved Golf Performance. Athl Ther Today 2010;15(4):22-6.

[53] Gulgin HR, Schulte BC, Crawley AA. Correlation of Titleist Performance Institute (TPI) level 1 movement screens and golf swing faults. J Strength Cond Res 2014;28(2):534-9.

[54] Key J. The pelvic crossed syndromes: a reflection of imbalanced function in the myofascial envelope; a further exploration of Janda's work. J Bodyw Mov Ther 2010;14(3):299-301.

[55] Okada T, Huxel KC, Nesser TW. Relationship between core stability, functional movement, and performance. J Strength Cond Res 2011;25(1):252-61.

[56] Morrison SD, Chaconas EJ. Power Development for Golf. Strength Cond J 2014;36(4):43-8.

[57] Spaniol FJ. Striking Skills: Developing Power to Turn. Strength Cond J 2012;34(6):57-60.